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ANALYTIC MATHEMATICAL MODELS OF TACTICAL MILITARY COMMUNICATIONS CHANNELS

QUARTERLY REPORT

JANUARY, 1973

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ANALYTIC MATHEMATICAL MODELS OF TACTICAL MILITARY COMMUNICATIONS CHANNELS

FIFTH QUARTERLY PROGRESS REPORT

1 July 1972 to 30 September 1972

Contract No. DAAB07-71-C-0292

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ABSTRACT

Burst distribution was derived using the generating function. However, this method is only practical for small values of K. A special case for K = 2 was carried out. The result agrees with that derived directly from the gap distributions. Numerical results for K = 2 have been obtained for the VHF channel.

Product codes were discussed and the probability of error for the product code was derived in terms of $P_\ell(m,n)$, the probability that m errors occurred in n bits with each bit ℓ positions apart from the next bit.

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SUMMARY

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Product codes were discussed and the probability of error for the product code was derived in terms of $P_{\ell}(m,n)$, the probability that m errors occurred in n bits with each bit ℓ positions apart from the next bit.

SECTION 2

MARKOV GAP MODELS

2.1. BURST DISTRIBUTIONS

In the Fourth Quarterly Progress Report [1] recursive expressions were derived for the burst distributions of the gap Markov model using the definition of a burst as a sequence of bits starting and ending in an error and separated from neighboring bursts by at least K error free bits. The resulting expression for the burst rate $p_b(m)$ is

$$p_b(m) = \sum_{i=0}^{K-1} f_i(m)P(K|i) \quad , \quad m \geq 2 \tag{1}$$

where $P(m|n)$ is the conditional gap distribution and where the $f_i(m)$ satisfy the recursive relations

$$f_i(m) = \sum_{j=0}^{K-1} f_j(m-i-1)[P(i|j)-P(i+1|j)] \quad , \quad m \geq i+3 \tag{2}$$

$$f_i(i+2) = \{\sum_{j=K}^{\infty} [P(i|j) - P(i+1|j)] [P(j)-P(j+1)]\} /P(K) \tag{3}$$

$$f_i(m) = 0, \quad m < i+2 \tag{4}$$

and where $P(m)$ is the unconditional gap distribution.

The relation given above may be implemented directly using the gap distributions of the channel as inputs, and the results may then be compared with the burst distributions obtained directly from the data to check the validity of the model. This procedure was performed for solid bursts (K=1) for both the VHF and the Tropo channels with excellent results [1]. The results for higher values of the parameter K are being processed. Alternatively, the generating function method may be used to solve the difference equation (2) with (3) and (4) as initial conditions. However, such a solution is practical only for low values of K unless the number of states of the model is reduced by using $P(m|n_1 \leq n < n_2)$ instead of $P(m|n)$ for all $n_1 \leq n < n_2$. Let $\tilde{f}_i(z)$ be defined by

$$\tilde{f}_i(z) = \sum_{m=0}^{\infty} f_{i-1}(m+i+1)z^{m+i} \quad , \quad i=1,2,\ldots,K \tag{5}$$

If (2) is substituted in (5) then

$$\tilde{f}_i(z) = f_{i-1}(i+1)z^i + \sum_{m=1}^{\infty} \sum_{j=0}^{K-1} f_j[m+i+1-(i-1)-1]z^{m+i}[P(i-1|j)-P(i|j)]$$

$$= f_{i-1}(i+1)z^i + \sum_{j=1}^{K} \sum_{m=1}^{\infty} F_{ij}f_{j-1}(m+1)z^{m+i} \qquad (6)$$

where we have defined

$$F_{ij} \stackrel{\Delta}{=} [P(i-1|j-1)-P(i|j-1)] \quad , \quad i,j = 1,2,\ldots,K \qquad (7)$$

Since $f_{j-1}(m+1) = 0$ for $(m+1) < (j-1+2)$, (6) may be reduced to

$$\tilde{f}_i(z) = f_{i-1}(i+1)z^i + z^i \sum_{j=1}^{K} F_{ij} \sum_{m=j}^{\infty} f_{j-1}(m+1)z^m$$

$$= f_{i-1}(i+1)z^i + z^i \sum_{j=1}^{K} F_{ij} \sum_{n=0}^{\infty} f_{j-1}(n+j+1)\, z^{n+j} \quad , \text{ for } n=m-j$$

$$= z^i \{f_{i-1}(i+1) + \sum_{j=1}^{K} F_{ij}\tilde{f}_j(z)\} \qquad (8)$$

which may also be written compactly as

$$[\Lambda\ (z) - F]\ \underline{\tilde{f}}(z) = \underline{a} \qquad (9)$$

where $\Lambda\ (z)$ is diagonal matrix whose elements are $(\frac{1}{z}, \frac{1}{z^2}, \ldots, \frac{1}{z^K})$, $\underset{\sim}{F}$ is a $K \times K$ matrix whose elements are F_{ij}, and the K-dimensional vectors $\underline{\tilde{f}}(z)$ and $\underline{a}$ have elements $\tilde{f}_i(z)$ and a_i respectively,

$$a_i = f_{i-1}(i+1) = \frac{1}{P(K)} \{P(i-1)-P(i) - \sum_{j=1}^{K} F_{ij}[P(j-1)-P(j)]\},$$

$$i = 1, 2, \ldots, K. \qquad (10)$$

Equation (9) may now be solved for $\underline{\tilde{f}}(z)$ and then the $f_i(m)$ may be obtained by using (5) which finally yields the burst rate $p_b(m)$ for $m \geq 2$. If F is nonsingular (which means that the conditional gap distributions are distinct) then the numerator of

$$\det|\Lambda(z) - F|$$

is a polynomial in z of degree $\frac{K(K+1)}{2}$. If its roots $\{\beta_i\}$ are also assumed to be distinct then the general form of the burst rate is given by

$$p_b(m) = \sum_{i=1}^{\frac{K(K+1)}{2}} K_i \beta_i^{\,m} \qquad m \geq 2 \tag{11}$$

The impracticality of this form for large values of K is immediately apparent as the number of terms increases rapidly. However, for larger values of K the conditional gap distributions are not available distinctly, and therefore the elements of F are no longer distinct. In that case the degree of the polynomial in z is reduced, and consequently the general form (11) has a smaller number of terms. The case where K = 1 has already been considered. The case where K = 2 will be discussed next both exactly and approximately using a reduced number of states.

2.2. SPECIAL CASE, K = 2

The solution (9) for K = 2 may be easily shown to result in the following expressions

$$\tilde{f}_i(z) = z^i \frac{\Delta i(z)}{\Delta(z)} \quad , \quad i = 1,2 \tag{12}$$

where

$$\Delta(z) = 1 - zF_{11} - z^2F_{22} + z^3 \left[F_{11}F_{22} - F_{12}F_{21}\right] \tag{13}$$

$$\Delta_1(z) = a_1 + z^2 \left[a_2F_{12} - a_1F_{22}\right] \tag{14}$$

$$\Delta_2(z) = a_2 + z[a_1F_{21} - a_2F_{11}] \tag{15}$$

$$a_i = f_{i-1}(i+1) = \frac{1}{P(2)} \left[p(i-1) - F_{i1}\, p(0) - F_{i2}p(1)\right], \; i = 1,2 \tag{16}$$

where

$$p(i) = [P(i) - P(i+1)]$$

are the unconditional gap probabilities. If $\Delta(z)$ is factored as follows

$$\Delta(z) = \prod_{j=1}^{3} (1-\beta_j z) \tag{17}$$

then the expressions for $f_i(m)$ may be obtained from (12) and (5), and are given by the expressions

$$f_i(m+i+2) = \sum_{j=1}^{3} A_{ij}\beta_j^{m+1} \quad , \quad i = 0,1, \quad m \geq 0 \tag{18}$$

where

$$A_{ij} = -\frac{\Delta_{i+1}(\beta_j^{-1})}{\Delta'(\beta_j^{-1})} = \frac{\Delta_{i+1}(\beta_j^{-1})}{F_{11}+2\beta_j^{-1}F_{22} - 3\beta_j^{-2}(F_{11}F_{22}-F_{12}F_{21})} \tag{19}$$

where $\Delta'(\beta_j^{-1}) = \frac{d}{dz}\Delta(z)\big|_{z=\beta_j^{-1}}$.

Therefore, the general expression for the burst rate is given by

$$p_b(2) = f_0(2)P(2|0) \tag{20}$$

$$p_b(m) = \sum_{j=1}^{3}\left[A_{0j}\frac{P(2|0)}{\beta_j} + A_{1j}\frac{P(2|1)}{\beta_j^{2}}\right]\beta_j^{m} , \; m \geq 3 \tag{21}$$

In order to simplify these expressions and reduce the number of states, the conditional distributions $P(i|0)$ and $P(i|1)$ will be assumed to be identical, and will be replaced by $P(i|0 \leq n \leq 1)$, i.e. $P(i|0)$ and $P(i|1)$ are approximated by

$$P(i|0,1) = \frac{P(i|0)p(0) + P(i|1)p(1)}{1-P(2)} \tag{22}$$

In this case the elements of F become

$$\begin{aligned} F_{12} &= F_{11} = 1 - P(1|0,1) \\ F_{21} &= F_{22} = P(1|0,1) - P(2|0,1) \end{aligned} \tag{23}$$

Similarly the a_i becomes

$$\begin{aligned} a_1 &= f_0(2) = \frac{1}{P(2)}\;\{p(0) - F_{11}\,[1-P(2)]\} \\ a_2 &= f_1(3) = \frac{1}{P(2)}\;\{p(1) - F_{22}\,[1-P(2)]\} \end{aligned} \tag{24}$$

The expression for $\Delta(z)$ reduces to

$$\Delta(z) = 1 - zF_{11} - z^2F_{22} = (1-\beta_1 z)(1-\beta_2 z) \tag{25}$$

with

$$\beta_{1,2} = \tfrac{1}{2}[F_{11} \pm (F_{11}^{\ 2} + 4F_{22})^{\frac{1}{2}}] \tag{26}$$

Finally, the $f_i(z)$ may be combined since $P(2|0)$ and $P(2|1)$ in (21) are replaced by $P(2|0,1)$, so that

$$\tilde{f}_1(z) + \tilde{f}_2(z) = \frac{z\Delta_1 + z^2\Delta_2}{\Delta(z)} = z\,\frac{a_1 + z\,a_2}{\quad z)} \tag{27}$$

From (1) and (5) the expression for $p_b(m)$ may be derived as follows

$$\tilde{f}_1(z) + \tilde{f}_2(z) = z\sum_{m=0}^{\infty} [f_o(m+2)z^m + f_1(m+2)z^m]$$

$$= \frac{z}{P(2|0,1)} \sum_{m=0}^{\infty} z^m p_b(m+2) \tag{28}$$

which with (27) and (25) yields

$$p_b(m+2) = \left[\frac{\beta_1 a_1 + a_2}{(\beta_1 - \beta_2)}\,\beta_1^{\ m} - \frac{\beta_2 a_1 + a_2}{(\beta_1 - \beta_2)}\,\beta_2^{\ m}\right] P(2|0,1)$$

$$= \frac{P(2|0,1)}{(\beta_1 - \beta_2)}\,[a_1(\beta_1^{\ m+1} - \beta_2^{\ m+1}) + a_2(\beta_1^{\ m} - \beta_2^{\ m})],\quad m \geq 0 \tag{29}$$

The expression (29) for $m = 0$ agrees with the expression given in (20) if $P(2|0)$ is replaced by $P(2|0,1)$. It is seen though that the number of the exponential terms in (29) has been reduced from three in (21) to two.

2.3. NUMERICAL RESULTS FOR THE VHF CHANNEL

Numerical results for $K = 2$ have been obtained for the VHF channel. In this case the gap data yielded the following distributions,

$P(1|0) = 0.6062$ $\qquad$ $P(1|1) = 0.5944$

$P(2|0) = 0.4063$ $\qquad$ $P(2|1) = 0.3884$

$p(0) = 0.3868$ $\qquad$ $p(1) = 0.1293$

Consequently the approximate values of F_{11} and F_{22} are

$F_{11} = 0.3977$ $\qquad$ $F_{22} = 0.2119$

so that the exponents β_i are given by

$$\beta_1 = 0.7003$$

$$\beta_2 = -0.3026$$

Which when substituted in (29) yields the following expression

$$p_b(m) = (0.07618)(0.7003)^{m-2} - (0.01016)(-0.3026)^{m-2} \text{ , } m \geq 2.$$

The expression for m = 1 is obtained separately as shown in (1) and should be in exact agreement with the data, as it does not involve the assumptions of the model. The result is

$$p_b(1) = 1 - \frac{P(2|0,1) [1-P(2)]}{P(2)} = 0.7475$$

which is identical to the burst rate obtained directly from the data. For the purpose of comparison to the data the expression for the anti-cumulative burst distribution $P_b(m)$ is obtained

$$P_b(m) = \sum_{k=m}^{\infty} p_b(k) = 0.2542(0.7003)^{m-2} - 0.0077(-0.3026)^{m-2} \text{ , } m \geq 2$$

Since both the coefficient and the root of the second term are small compared to the first term, its effect is negligible for m ≥ 5, so that an approximate expression for $P_b(m)$ is given by

$$P_b(m) \approx 0.2542(0.7003)^{m-2}$$

The approximate expression for the burst distribution given from the model is shown in Fig. 1 together with the distribution obtained directly from the data. It is seen that it is in excellent agreement up to m = 8. For higher values of m the approximation is still relatively very good in view of the fact that the probabilities involved are very small. The exact expression of (21) is expected to yield a better approximation to the data as it has an additional exponent which would help improve the fit. Definite statements concerning the validity of the model may be made only after the comparison for several values of K has been performed.

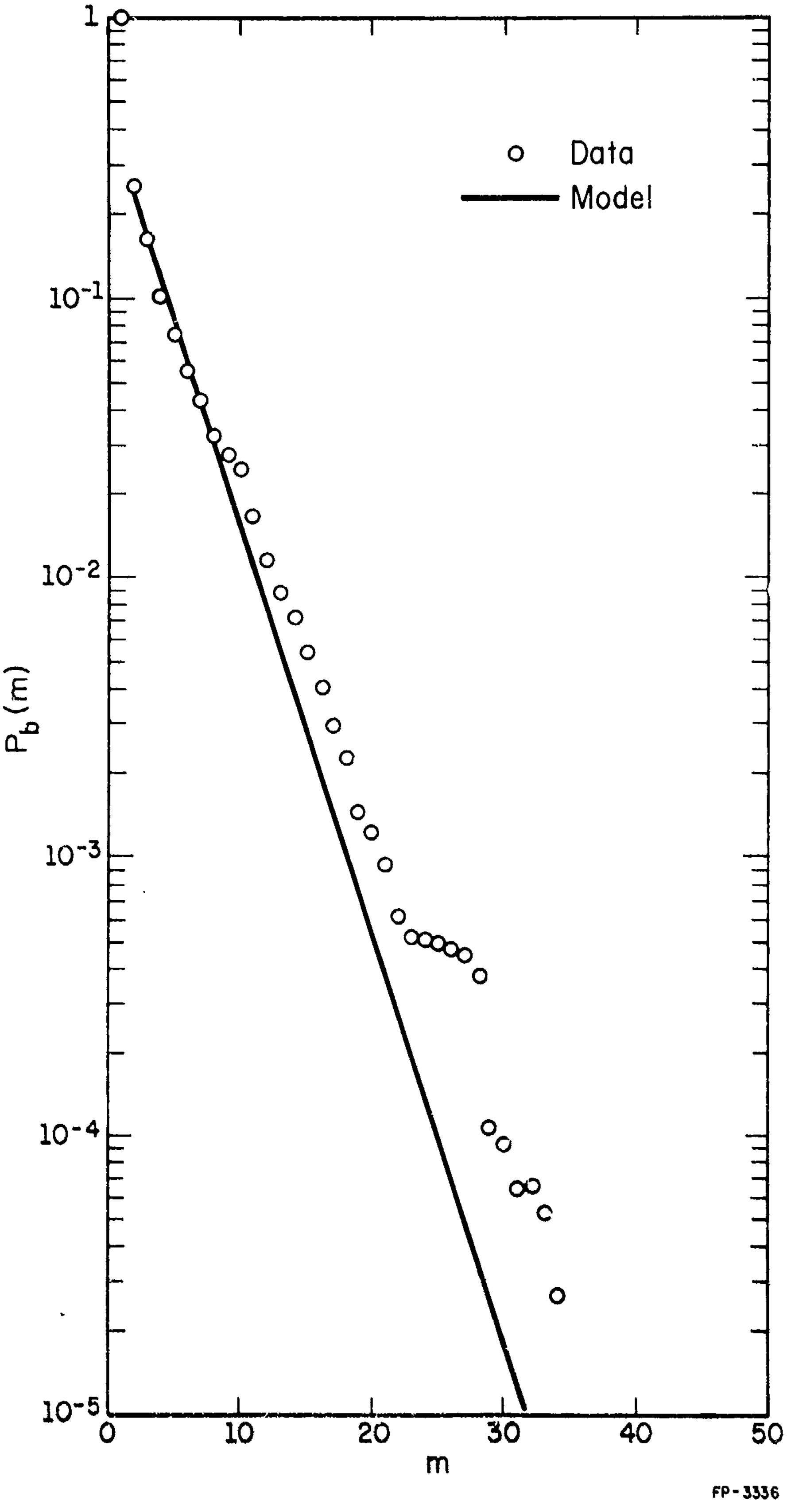

Figure 1. The burst distribution $P_b(m)$ for the VHF channel for K = 2.

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[1] R. T. Chien, F. P. Preparata, A. H. Haddad and C. L. Chen, Fourth Quarterly Progress Report, Contract No. DAAB-07-71-C-0292 for U. S. Army Electronics Command, Fort Monmouth, New Jersey, October 1972.

SECTION 3

CODE EVALUATION

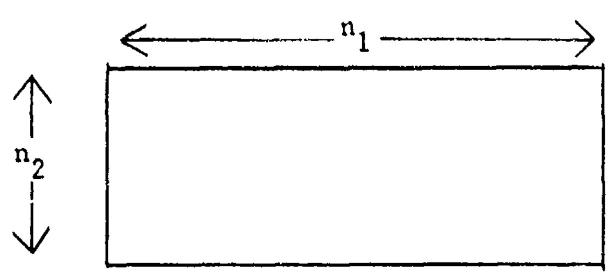
3.1. PRODUCT CODES

Product codes [1] are attractive in many types of data communication systems. They are capable of correcting simultaneously random errors and burst errors. Although their implementation is slightly more complicated than that of interleaved codes, product codes are considerably more powerful than interleaved codes.

The decoding of a product code, first proposed by Elias, can be reduced to the decoding of its subcodes of shorter code length. In this type of decoding, rows are decoded first, then columns and if necessary code words of higher dimensions are decoded. Naturally, majority-logic decoding can be applied to the decoding of the subcodes. Furthermore, it has been shown recently that the information about the decoding of row codes can be carried over to the decoding of the column codes, thus a product code is capable of correcting all the error patterns guaranteed by the minimum distance in addition to many other correctable errors [2].

The performance of a product code on a real channel depends on the decoding scheme used. We will consider only the two-dimensional product codes. Furthermore, a cascade decoding [3] scheme will be used. This decoding scheme can be simply implemented. In addition, the probability of error can be calculated from the statistics of the channel data.

A two-dimensional (n_1n_2,k_1k_2) product code is the direct product of an (n_1,k_1) row code and an (n_2,k_2) column code. Let t_1 and t_2 be the error correcting capabilities of the row code and column code, respectively. A code word of the product code can be arranged in a two-dimensional array so that every row forms a code word of the (n_1,k_1) code and every column forms a code word of the (n_2,k_2) code. The array is depicted as follows:



Let us assume that a code word is transmitted column by column. At the receiver, rows are decoded according to the decoding scheme for (n_1,k_1) code. Columns are decoded according to the decoding scheme for (n_2,k_2) code after all rows have been decoded.

Let $P_\ell(m,n)$ be the probability that m errors occurred in n bits, with each bit ℓ positions apart from the next bit. $P_\ell(m,n)$ can be obtained directly from the channel data.

The probability of m errors in a row is by our definition equal to $P_{n_2}(m,n_1)$. Since the row code is capable of correcting t_1 errors. The probability of decoding error in a row is

$$
\begin{aligned}
S &= \Pr\{\text{more than } t_1 \text{ errors in a row}\} \\
&= P_{n_2}(> t_1, n_1) \\
&= \sum_{i=t_1+1}^{n_2} P_{n_2}(i,n_1) \qquad (1)
\end{aligned}
$$

Here the bounded-distance decoding of the row code is assumed. The probability of correctly decoding is

$$
\begin{aligned}
1 - S &= \Pr\{\text{at most } t_1 \text{ errors in a row}\} \\
&= P_{n_2}(\le t_1, n_1) \\
&= \sum_{i=0}^{t_1} P_{n_2}(i,n_1) \qquad (2)
\end{aligned}
$$

Let us assume that the probability of decoding error in a row is made independent of the other row. Thus S is a constant, independent of row code words. The probability of j errors in a column is obtained from the binomial distribution

$$
P(j,n_2) = \binom{n_2}{j} S^j (1-S)^{n_2-j} . \qquad (3)
$$

The probability of error for the product code is then

$$
\begin{aligned}
P_e &\le \sum_{j=t_2+1}^{n_2} P(j,n_2) \\
&= \sum_{j=t_2+1}^{n_2} \binom{n_2}{j} S^j (1-S)^{n_2-j} \\
&= 1 - \sum_{j=0}^{t_2} \binom{n}{j} S^j (1-S)^{n_2-j} \qquad (4)
\end{aligned}
$$

In the next period, several product codes will be evaluated for their performance according to Equation (4).

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[2] S. M. Reddy, "On Decoding Iterated Codes," IEEE Trans., IT-16, pp. 624-627, September 1970.

[3] N. Abramson, "Cascade Decoding of Cyclic Product Codes," Technical Report, Department of Electrical Engineering, University of Hawaii, Honolulu, Hawaii, 1967.

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13. ABSTRACT

Preliminary comparison of the burst data to the model parameters obtained from the gap distributions were performed for K=2. Definite statements concerning the validity of the model may be made only after the comparison for several values of K has been performed.

Product codes were investigated and theoretical performance equations were derived.

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